University of Colorado
Boulder

Interdisciplinary Telecom Program
Engineering Office Tower 311
530 UCB
Boulder, Colorado 80309-0422

t 303 492 8475
f 303 492 1112
itp@colorado.edu

Interdisciplinary Telecom Program's
Hands-On Wireless Network Communications Curriculum

Overview

The Interdisciplinary Telecommunications Program (ITP) at the University of Colorado in Boulder has developed a focused strategy to supplement theoretical radio transmission and digital communications concepts with hands-on laboratory exercises utilizing software defined radio (SDR). In conjunction with ITP lecture-based courses to provide a solid foundation in digital communication theory, SDR-based laboratory exercises will simultaneously enable our students to synthesize several fundamental concepts utilizing the latest, modern, communications systems technologies. The ITP Wireless Communications Laboratory will function as a classroom for lectures, a laboratory for experimentation and as a shared research facility for students and faculty.

The ITP Wireless Communications Laboratory ("Wireless Lab") will benefit both training and research for graduate students in the existing M.S. ITP Wireless Networking track and Ph.D. program, as well as provide a properly instrumented facility to support continuing professional development for commercial and industrial professionals seeking to augment their conceptual understanding and skills development.

The ITP Wireless Lab provides an ideal setting to teach students and continuing professionals, in a hands-on fashion, key technical skills required to understand, build, test, and analyze both analog and digital wireless communications concepts. State-of-the-art technology and facilities are employed to introduce both students and practicing professionals to common issues encountered in modern wireless communications systems.

Introduction

Modern society is increasingly dependent upon wireless digital communications systems to perform nominal daily tasks in the workplace, at home, for travel and navigation, social media networking, entertainment, public safety and homeland security, and even for military operations. In 2015 annual revenues for the telecommunications sector reached \$1.3 trillion.[1] In the Unites States telecommunications revenues (retail and wholesale) exceeded \$250 billion with a compounded annual growth rate (CAGR) of 6.19%. The

[1] U.S. Market Telecommunications Report, 2016

expansion of these markets is not slowing as evidenced by the recent FCC spectrum auction in January of 2015 where a 500 MHz block of spectrum rights was sold for a staggering amount of $44.6 billion.[2] Despite the massive growth in fiber-to-the-home networks, it is expected that wireless networks will continue to provide a major impetus to the telecom industry. Wireless network standards are continuously evolving around the globe to offer faster speed. After significant growth of the next-generation 4G LTE network deployment, the LTE-A (Long-Term Evolution Advanced) wireless network standard is gradually gaining a strong foothold worldwide.[3]

Wireless communications courses are taught in most engineering and computer science curricula worldwide, where the main emphasis has traditionally focused on the theoretical concepts and constructs of communications. While it is essential that students learn the theory of communications, this is inadequate to prepare them for their careers in commercial industries. This is due to the fact that there are several practical challenges in designing and implementing wireless communications systems that are overlooked, or hand-waved, when focusing only on theory.[4] Software defined radio can be utilized as a educational mechanism to reinforce the theory with hands-on learning. An SDR is a communications platform that utilizes software for implementing digital communications algorithms and associated processing.

Software defined radio is a rapidly evolving field that is driving the development of and innovation in communications technology, and promises to significantly impact all communications sectors. Entities developing these SDR systems require a trained workforce that has been prepared with the mindset, knowledge, skills, and tools necessary to both address the system (breadth) and technical (depth) aspects of SDR systems. Developing SDRs necessarily involves a collection of disciplines including, but not limited to, electromagnetics, radio-frequency engineering, communications, digital signal processing, embedded systems, computer programming, and systems engineering. SDR can be employed as an integrative construct that facilitates systems thinking and fosters cross-domain learning via peers.[5]

The Wireless Lab will function as a classroom for lectures, a laboratory for experimentation and as a shared research facility for students and faculty. It will benefit both training and research for graduate students in the existing M.S. ITP Wireless Networking track and Ph.D. program, as well as provide a properly instrumented facility to support continuing professional development (CPD) for commercial and industrial professionals seeking to augment their conceptual understanding and skills development. By prototyping and evaluating actual digital communications systems capable of performing "over-the-air" wireless data transmission and reception, students can attain a first-hand understanding of

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[2] Wall Street Journal, January 26, 2016

[3] Zacks Equity Research, September, 2014.

[4] El-Hajjar, E., Nguyen, Q., Maunder, R., Ng, S., "Demonstrating the Practical Challenges of Wireless Communications Using USRP", *IEEE Communications*, May, 2014.

[5] Bilen, S. G. et al, *IEEE Communications*, May, 2014.

the design trade-offs and issues associated with these systems, as well as gain a sense of actual "real-world" behavior.

This document provides an overview of ITP's detailed plans for implementing a Wireless Lab featuring multiple software defined radios along with modern spectrum analyzers to support the education and research objectives of the Wireless Networking Track for M.S. students and the PhD program. The first section describes the academic and research objectives of the Wireless Lab. The next section describes in more detail the specific laboratory exercises to achieve the academic and research objectives. Finally, we describe the state-of-the-art technology to be built into the Wireless Lab to support the required learning objectives and provide an estimate of the associated resources and costs.

Wireless Communications Laboratory Objectives

The Wireless Lab serves five primary objectives for ITP and its students:

- Enable students to develop systems engineering skills in the field of wireless communications;
- Enable students to gain first-hand knowledge and practical skills involving digital communications systems;
- Facilitate cross-domain learning via the peer learning process;
- Enable and facilitate research activities associated with the telecommunications industry and relevant national labs (e.g., NASA, NIST, FirstNet, NSF, DARPA, DoD, etc.)
- Serve as a state-of-the-art facility with modern equipment to support ITP Capstone projects

Achieving these goals requires adequate wireless networking equipment, an efficient learning environment, and well-organized laboratory exercises that enable, and inspire, student participation and learning. Importantly, the hands-on learning emphasis must be integrated and supported throughout the duration of the Wireless Networking Track curriculum.

Student Education - An SDR-focused approach to hands-on learning in the ITP Wireless Networking Curriculum

The integration of software defined radio in the Wireless Networking Track curriculum that emphasizes a "hands-on" laboratory component will significantly enhance the educational breadth and depth of ITP students pursuing a Wireless Networking Track degree. Pedagogical emphasis in the synthesizing of signals, systems, and information (SSI) concepts taught in class is supplemented by the implementation of theoretical constructs in actual prototype systems and conducting real-time "over-the-air" wireless communication system experiments. Given the complexity of these modern digital communication systems, especially those based on SDR technology, it is anticipated that the students will not only employ the fundamental concepts from courses within the SSI concentration but also integrate fundamental concepts from other areas of engineering including computer engineering, electromagnetics, control theory, and analog/RF circuit design.

To overcome the significant learning curve that is often associated with the initial usage of SDR technology, ITP Wireless Lab exercises are devised using the work flow shown in Figure 1, where the necessary skills required to successfully complete a laboratory experiment is gradually built up. Specifically, each laboratory experiment starts off with the theoretical preparation and the pre-laboratory exercises in order to ensure that the students are familiar with the key concepts before they commence with the actual implementation and experimentation process. Once the theoretical foundations have been established, the students are then responsible for designing digital communication systems and evaluating their implementations within a computer simulation environment such as LabView or GNU Radio. The rationale for the computer simulations is to ensure the students observe the operational behavior of a digital communication system within a controlled environment before conducting real world "over-the-air" experiments, which possess numerous non-ideal characteristics.

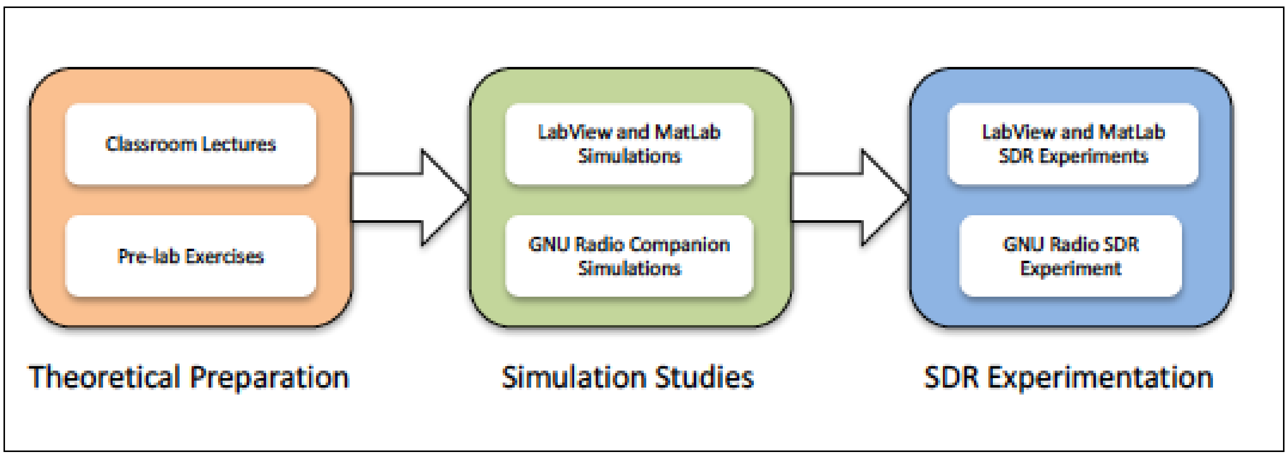

Figure 1 - Workflow template to be employed when designing SDR exercises in wireless networking.

Once the skill set of the students has been reinforced by the combination of theoretical preparations and simulation studies, they are ready to commence experimentation with digital communication systems operating within actual wireless environments. At this stage in the laboratory experiment, the students should be familiar with the behavior of the digital communication systems that will be implemented, which will be of valued assistance when debugging their designs. At this stage in the laboratory experiment, the students will be exposed to software tools that would enable them to utilize the SDR platforms.

Consequently, this curriculum should ultimately provide ITP students a systems-level understanding (breadth) of a modern digital communications wireless network while focusing on several key technology-related aspects (depth) in the design and implementation of these systems.

The expected high-level learning outcomes for this SDR-based digital communication systems curriculum is designed to enable students who successfully complete the laboratory exercises distributed throughout the Wireless Networking Track to:

- Implement an end-to-end wireless data transceiver capable of performing "over-the-air" digital transmission.
- Understand the advantages and limitations of available digital technology when constructing SDR systems.
- Compare symbol and bit error probabilities of common digital communication systems in additive white Gaussian noise (AWGN) channels between theoretical, computer simulated, and empirical experimentation.
- Implement the optimum receiver structure for digital transmission through an AWGN channel.
- Devise high-speed wireless data transmission approaches based on the concept of multicarrier modulation.
- Understand how to characterize and identify various digital transmissions based on their frequency representation.

Student Education - Pedagogical Motivation Detail

As shown in Figure 2, a typical wireless communications system will have a signal source, where source coding is applied to the signal in order to remove any redundancy in the source data. After source coding, the data bits are channel coded as shown in Figure 2, where channel coding is used for error detection and correction at the receiver. After channel coding, the data bits are mapped to symbols in the modulator, the output symbols of which are passed through an analog processing block before transmission in the channel. After transmission in the channel, as shown in Figure 2, the reverse processing of the transmitter is applied in the receiver.

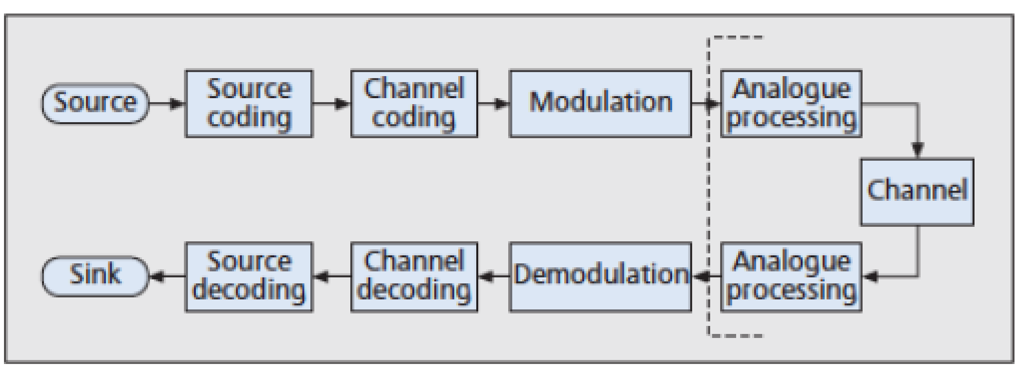

Figure 2 - Typical communications systems components.

Following are a list of several challenges in communications systems, which the students would be able to understand while using software defined radio.

Pulse shaping: The digital signal output of the modulator in Figure 2 cannot be transmitted easily over the wireless channel and hence needs to be mapped to an analog waveform that can be. This involves mapping the complex symbols output of the modulators of Figure 2 to an analog pulse train for transmission over the wireless channel. Then the receiver would perform an analogous operation to recover the complex symbols from the received pulses using a matched filter. Students normally learn about pulse shaping and the characteristics of a Nyquist system; however, they would not fully understand its implications due to the lack of practical implementation in the curriculum. Additionally, students would understand the importance of up-sampling and down-sampling in a transceiver more when they need to design a filter, since up-sampling is needed in order to allow for simpler filter implementation, where increasing the sampling frequency will relax the sharp cutoff requirements on the filters.

Bandwidth and data rate: Students normally study the importance of bandwidth in communications systems and its relation with the data rate via the Nyquist theorem. However, they do not learn how these can be used in practical systems and how they can be related to the processor speed running the receiver, for example.

Frame detection: The data is practically transmitted in frames with predefined structure, and it is essential for the decoder to know the beginning of a frame to be able to decode the signal. In practice, due to propagation and signal processing delays, the location of the beginning of the frame is unknown. Hence, detecting the beginning of a frame forms an integral part of any communications receiver, which can be considered as part of the receiver synchronization.

Timing recovery: When the signal is received, it is a complicated analog signal that should be sampled before recovering the digital data. Wireless channels introduce attenuation, phase shift, and time delay, which are unknown to the receiver, and the receiver needs to find the correct sampling point to be able to sample the received analog signal. This aspect of wireless system design is often ignored in baseband simulation; hence, the utilization of software radio will enable students to learn the importance of this phenomena in communications products. A related, additional, challenge includes the offset between the sampling rates at the transmitter and the receiver, which may also be variable. Hence, sampling frequency offset estimation as well as tracking the variation in this offset need to be considered when designing communications receivers.

Carrier recovery: Before sampling the received signal, the receiver down-converts the received analog signal to baseband, where the receiver must know the carrier frequency and phase of the received signal for successful demodulation. This is normally done via an oscillator, whose frequency is matched to the transmitter's carrier frequency. However, the receiver should estimate the phase and carrier frequency offsets introduced by the wireless channel and the imperfections in the circuitry. Furthermore, the carrier frequency offset may vary with time; hence, tracking the carrier frequency offset is another important challenge for designing communications receivers.

Channel state information estimation: In order to perform correct equalization, coherent wireless receivers need to know the channel, which is normally estimated by the receiver. Hence, to facilitate channel estimation, pilot symbols, which are known at the receiver, are transmitted periodically. Additionally, random noise is normally added to the signal in the receiver, which is normally modeled as Gaussian noise; and when soft-decoding is employed, the receiver should also estimate the noise variance in order to be able to implement soft demodulation.

Finally, there are several other considerations when designing wireless systems, including up-conversion at the transmitter and down-conversion at the receiver, sampling and quantization, input signal level measurement, automatic gain control (AGC), and common phase error cancellation that are highlighted when constructing over-the-air wireless communication systems.

In summary, wireless communication is now used in most aspects of our lives, and is taught in undergraduate and postgraduate curricula with more focus on theory than application and implementation. Students mainly focus on simulations of communications systems making several simplifying assumptions, which mainly ignore most of the above-mentioned practical aspects of transceiver design. The goal of the Wireless Lab is to introduce SDR in the ITP Wireless Networking courses (see Figure 3) to teach digital communications from an implementation point of view complimenting the traditional theoretical-focus pedagogy of communications theory.

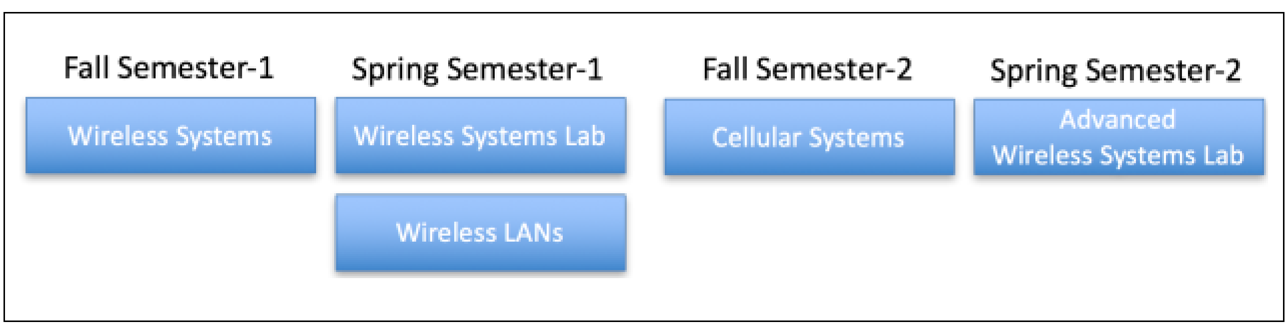

Figure 3 - Wireless Networking core courses to employ/emphasize SDR laboratory exercises.

Research Support

The ITP Wireless Lab (see Figure 4 below) will serve as a wireless networking communications research facility, supporting sponsored research activities and serving as a state-of-the-art facility to support ITP Capstone Projects.

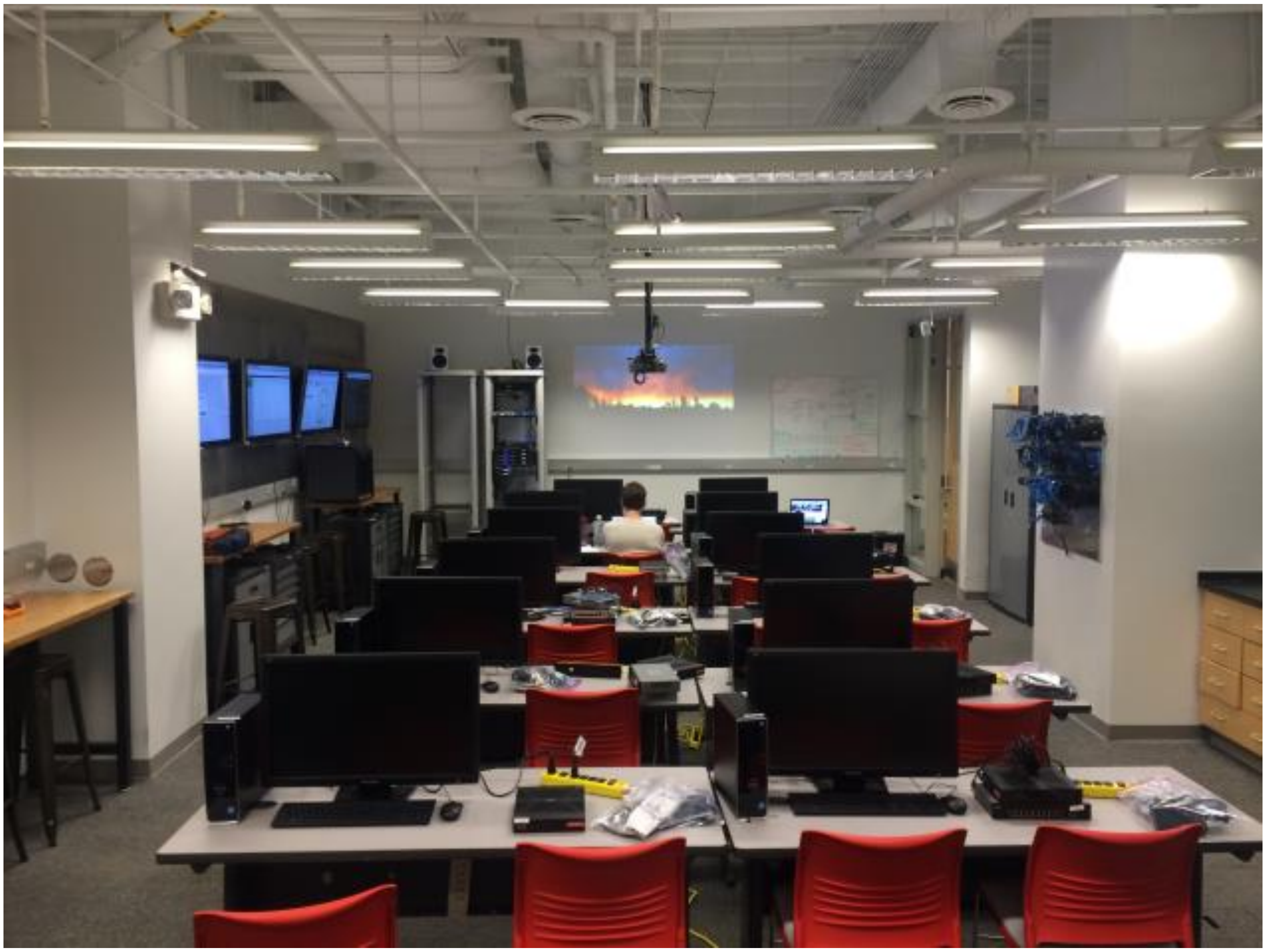

Figure 4 - The combined Wireless Lab and Security Operations Center within CU-Boulder ITP.

While a wide array of sponsored research is envisioned to be supported, the initial focus will be upon supporting advanced wireless and cellular networking in support of

- Public Safety sector (e.g., NIST, FirstNet, APCo, etc.); and
- Space Communications sector (NASA)

with specific emphasis upon mobile wireless communications networks including LTE, LTE-U, LTE Advanced, and WLAN technologies including 802.11.n, ac, ad, ax.